The "Compact Adaptable Microwave Limb Sounder" (CAMLS) project – first light results and future plans

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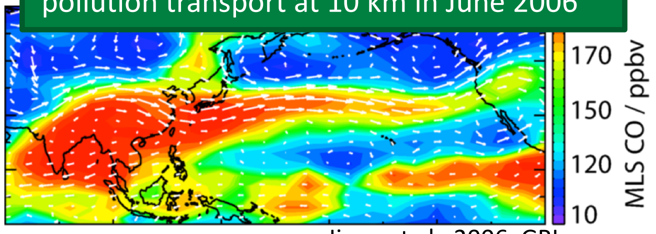
CAMLS science motivation – the "UT/LS"

Compact Adaptable Microwave Limb Sounder

- The CAMLS family of instruments makes measurements needed to address key outstanding issues associated with the composition and structure of Earth's upper troposphere and lower stratosphere (UT/LS hereafter)
  - The ~10 km to ~20 km altitude region
- It is in this region where:
  - Radiative forcing from water vapor (the strongest greenhouse gas) and ozone is greatest
  - Winds are fast, and chemical lifetimes are long, promoting global transport of greenhouse gases and pollutants (see upper figure)
  - Climate (and chemistry-climate) models continue to poorly represent key processes that control water vapor, composition and clouds (see lower figure)

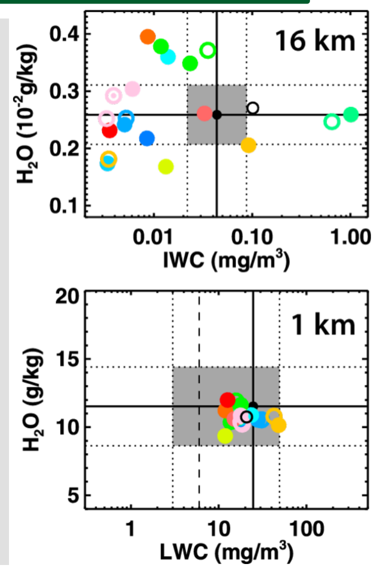
Aura MLS observations of long-range CO pollution transport at 10 km in June 2006



Jiang et al., 2006, GRL

A-Train observations show that climate models perform poorly in the upper troposphere (top panel) compared to the lower troposphere (bottom panel)

x-axes are cloud ice
y-axes are water vapor
Black points are observations
Grey shading denotes measurement uncertainty
Colored points are climate models
Top panel shows 16 km altitude observations from Aura MLS
Bottom panel shows 1 km altitude observations from AIRS & CloudSat



Jiang et al., 2012 JGR

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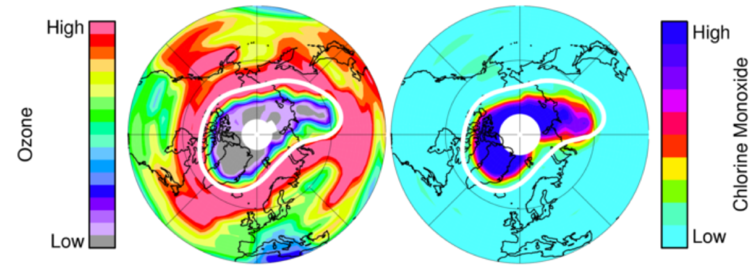
CAMLS science – issues in the stratosphere

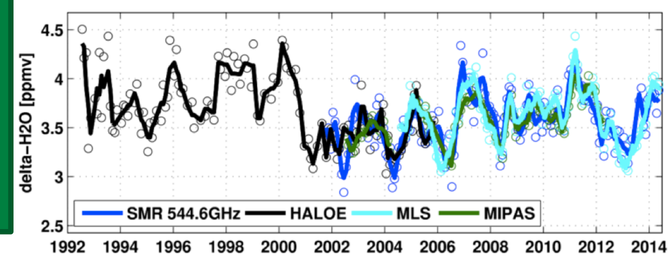
- In the stratosphere (~15 – 50 km), high levels of atmospheric chlorine continue to destroy ozone, and there are recent indications of continuing "rogue" production of ozone-depleting CFC-11
- Unexpected and incompletely explained changes in stratospheric humidity in the past decade have contributed significantly to surface temperature changes
- Interest is growing in "geoengineering" approaches to tackling climate change, including the injection of sulfate aerosols into the stratosphere, any study of which must be informed by observations

Aura MLS observations of ozone (left) and chlorine monoxide (right) – the primary agent of ozone destruction – at ~20 km in March 2011, a period of unprecedented ozone loss in the northern hemisphere



Manney et al., 2011, Nature

Tropical water vapor at ~16 km from Aura MLS and other sensors, showing unexpected sudden declines in 2000 and 2012



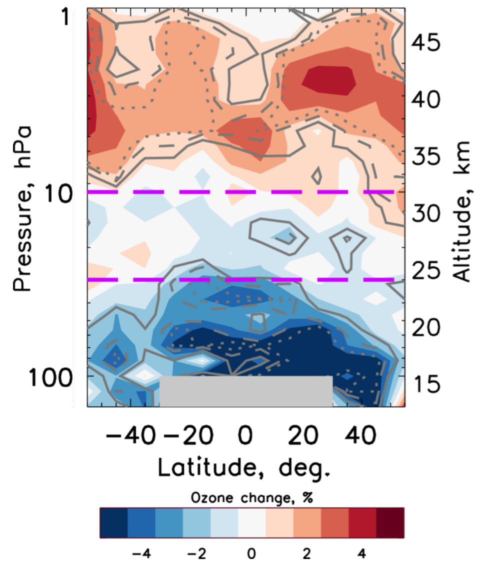
Urban et al., 2014, EOS

Illustration of various possible approaches to injecting sulfate aerosol into the stratosphere, in order to reduce surface heating

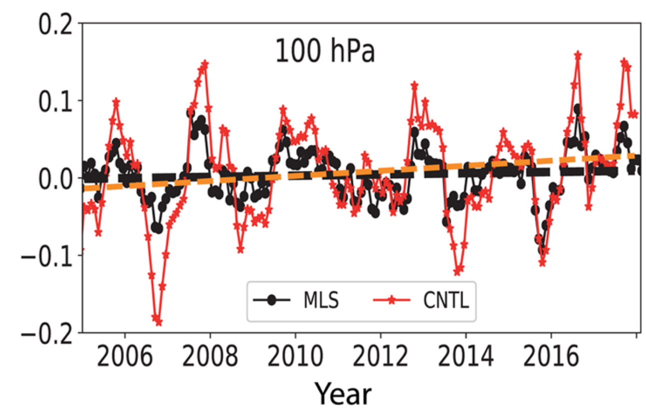
Robock, 2009, GRL

Update: Ozone recovery in a changing climate

- Signs of recovery in the ozone layer are now clear in the upper stratosphere (~35–50 km)
- However, in the lower stratosphere, and in polar regions, strong interannual variability hampers detection of recovery
- For example, a recent paper [*Ball et al.*, *ACP*, 2018] found a statistically significant decline in midlatitude lower stratospheric ozone from 1998–2016 (upper figure)
- However, a later study [*Chipperfield et al., GRL,* 2018] showed that extending the record by including Aura MLS observations in 2017, when ozone increased strongly, made the trend non-significant (lower figure)
- These findings underscore the need for continued long-term vertically resolved global measurements of ozone to ensure recovery is proceeding as expected
- Ongoing measurements of other species are also needed to separate the dynamical and chemical influences on the long-term trend in ozone (and water vapor)



1998–2016 zonal mean ozone change from multiple satellite sensors. Note the decline found in the lower stratosphere



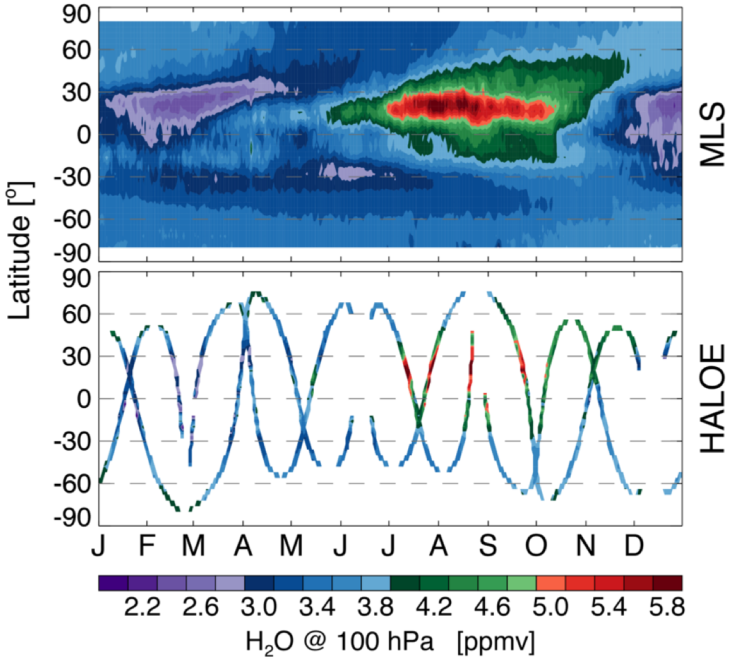
MLS 100 hPa (~16 km) ozone (35–50S) showing an uptick in 2016

Approaches to measuring the UT/LS from space

- Nadir sounding instruments (at any wavelength) have poor (~6 km at best) vertical resolution when measuring composition of the upper troposphere and stratosphere
- GPS radio occultation measures stratospheric temperature profiles, but GPS water vapor measurements do not extend above the mid-troposphere
- Spaceborne Lidar approaches are hindered by insufficient laser power
- Accordingly, spaceborne middle atmosphere composition sounders to date are are either:

Passive limb sounders measuring thermal emission (infrared or microwave) or solar scatter (near IR, visible, or ultra violet), scanning the limb vertically to give daily near-global coverage (daytime only for solar scatter). Microwave limb sounders can see through aerosol and all but the thickest clouds

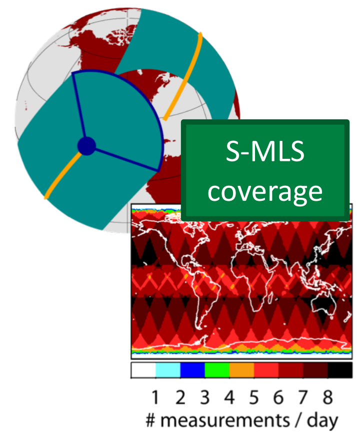
Solar (and/or lunar/stellar) occultation sounders measuring atmospheric absorption each orbital sunrise/sunset (or moon/star rise/set). They have good vertical resolution (~1 km) and excellent precision (for solar), but only make a small number of measurements per day, at drifting latitudes



Zonal mean ~16 km H_2O vs. time as measured using limb emission (upper) and solar occultation (lower) sounders

High level CAMLS project goals

- The goal of the CAMLS IIP-2013 project is to develop state-of-the-art receiver/spectrometer technologies that can form the core of:
  - A “Continuity MLS” instrument to extend and augment the record from Aura MLS
  - A “Scanning MLS” that, using a cooled receiver and 2D scanning limb antenna (IIP-2010) can measure a wide swath with 50x50 km spatial resolution
- CAMLS uses a single 340 GHz receiver to measure nearly all the species measured by Aura MLS over five spectral regions
- Digital spectrometers provide ~1.2 MHz spectral resolution within a +/–20 GHz IF, avoiding the calibration challenges associated with individual discrete analog channels
- Overall a CAMLS-based “Continuity MLS” instrument can be accommodated within 20kg, 100W, 70cm antenna size, 0.01m^3 electronics
  - Aura MLS was 350kg, 370W, 1.6m antenna, ~1m^3 electronics

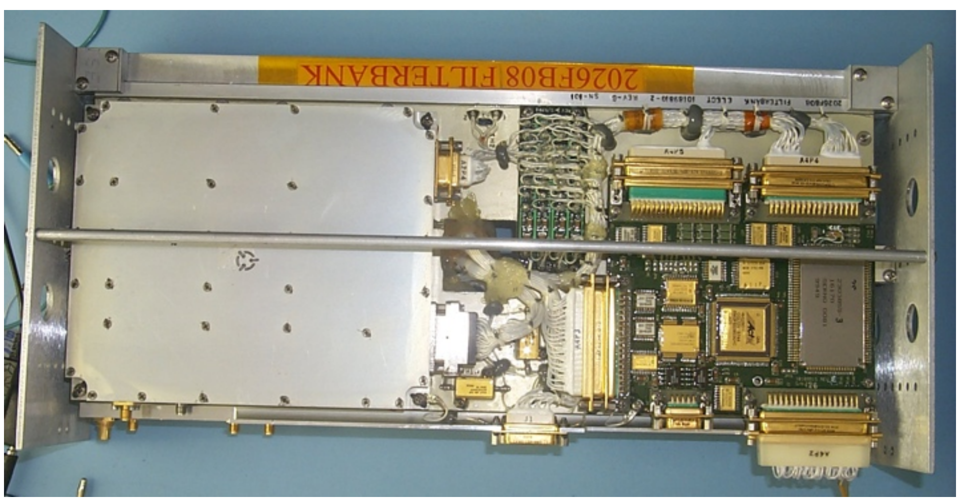


CAMLS measurements: T/GPH, O_3, H_2O, CO, HNO_3, H_2CO, N_2O, ClO, HOCl, CH_3Cl, BrO, HO_2, CH_3CN, SO_2, Cloud ice, others…

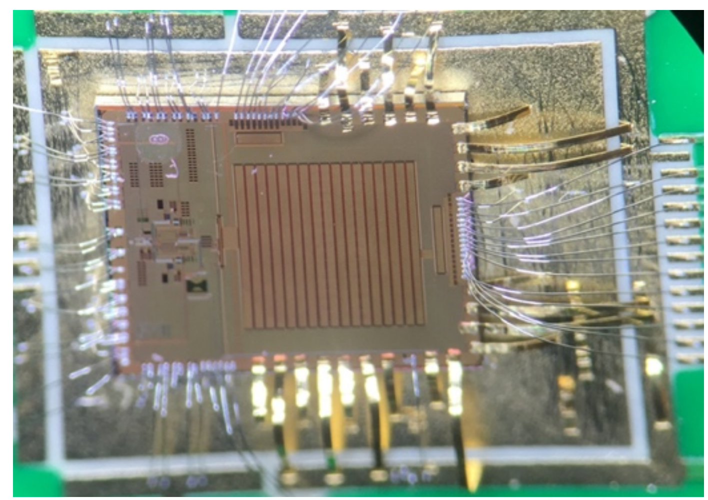
CMOS-based single chip digital spectrometers

- The past decade has seen dramatic advances in the technology associated with the “spectrometers” needed for an MLS-like instrument
  - These advances have been driven by the needs of the communications industry
- Aura MLS has over 500 individual analog “channels” each consisting of inductors, capacitors, etc.
- These can now be replaced with a handful of far more capable single chip devices

An assembly holding two 25-channel ~1.5 GHz spectrometer from Aura MLS (~4 kg, ~40 cm, ~5 W)



A 4096-channel 3 GHz spectrometer on a single chip (~5mm, ~1.5 W)

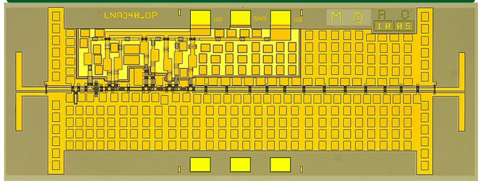


New 340 GHz sideband separating receiver

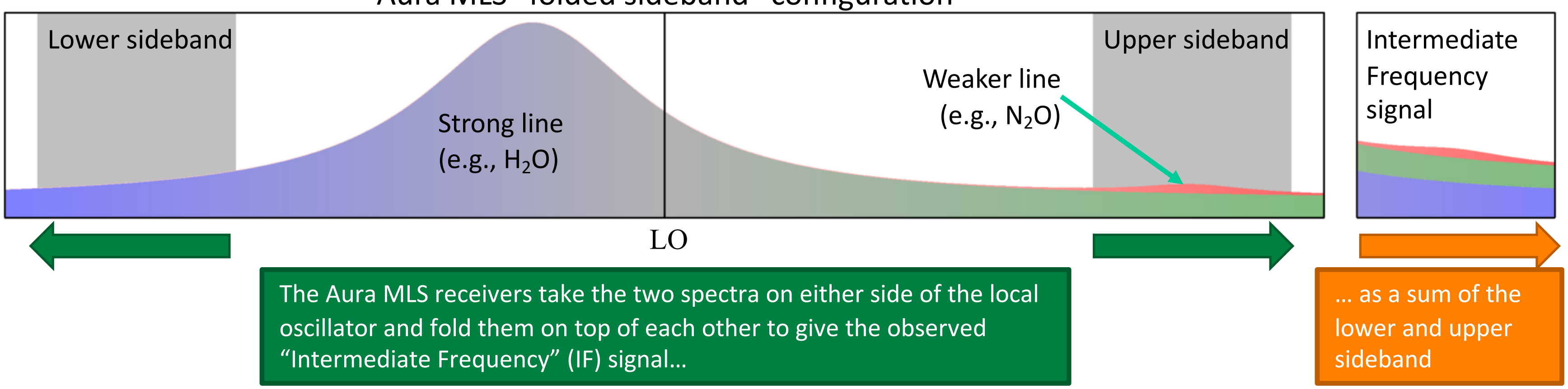
Compact Adaptable Microwave Limb Sounder

- While Aura MLS observed in five spectral regions (118, 190, 240, 640, and 2400 GHz) a simpler 340 GHz-only instrument could measure nearly all the Aura MLS species
- New “Low Noise Amplifiers” enable receivers providing comparable performance to older “Schottky diode” devices at room temperature, but also provide greatly improved signal to noise when cooled
- Another important advance is “sideband separation”, which avoids an unfortunate ambiguity encountered with MLS measurements in the upper troposphere and lower stratosphere

Microscope image of 340 GHz LNA



Aura MLS “folded sideband” configuration



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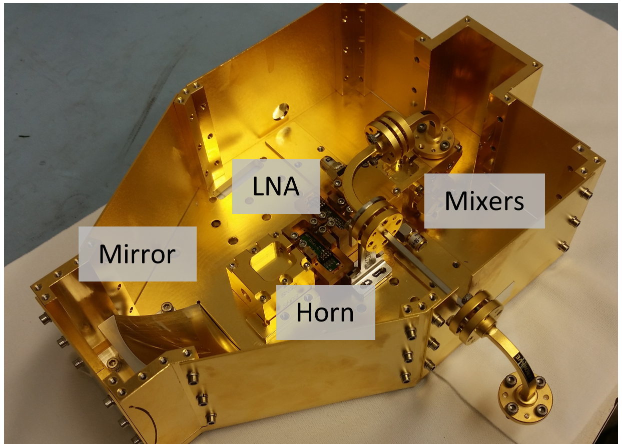
CAMLS key subsystems and components

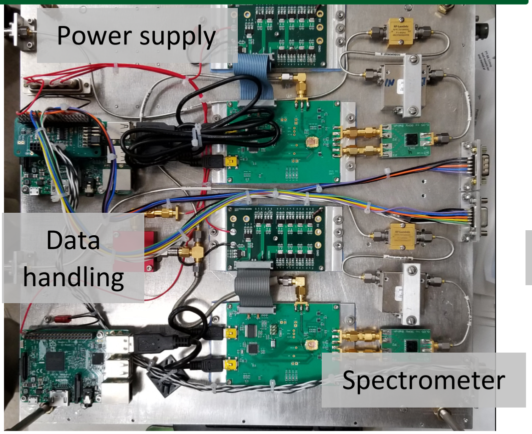
Compact Adaptable Microwave Limb Sounder

- The "Compact, Adaptable Microwave Limb Sounder" (CAMLS) project is developing both these technologies, and upgrading the previously developed "Airborne Scanning Microwave Limb Sounder" (A-SMLS) instrument to test them
- Test flights on the NASA ER-2 are now planned for early 2019 (delayed by aircraft availability)

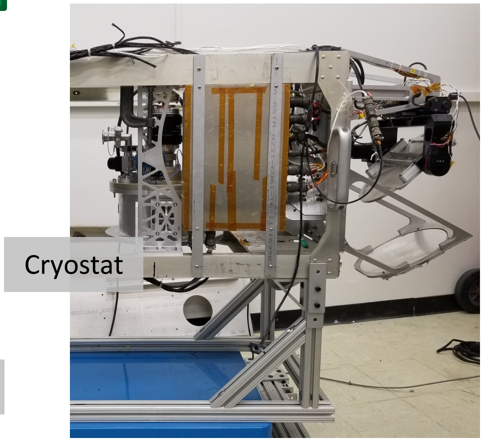
340 GHz receiver assembly integrated into "Cold box"



Spectrometer "slice" containing two CMOS spectrometer chip plus power supply and data handling (RaspberryPi) boards.



Front part of A-SMLS instrument, with 340 GHz CAMLS receiver in cryostat



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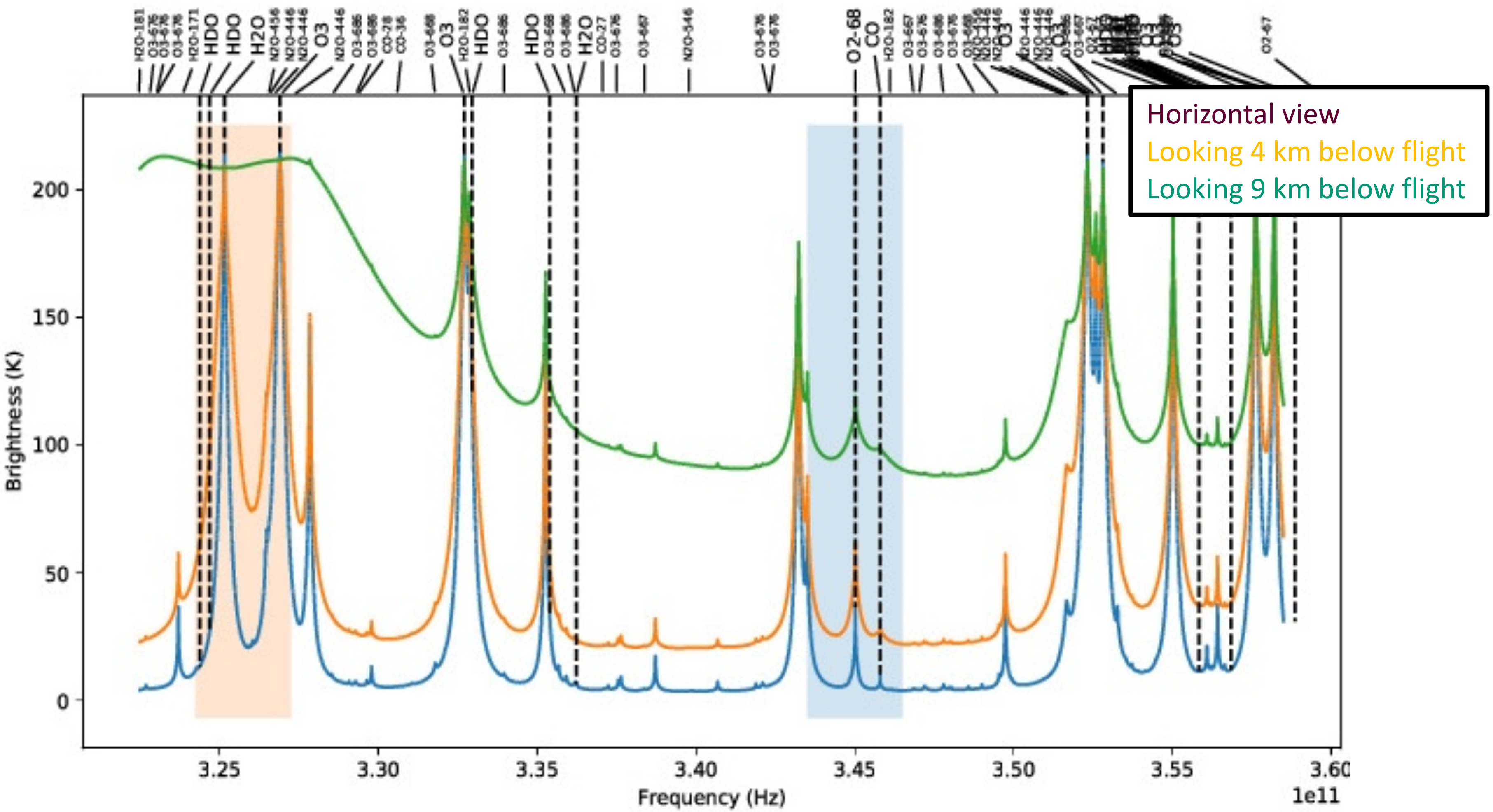
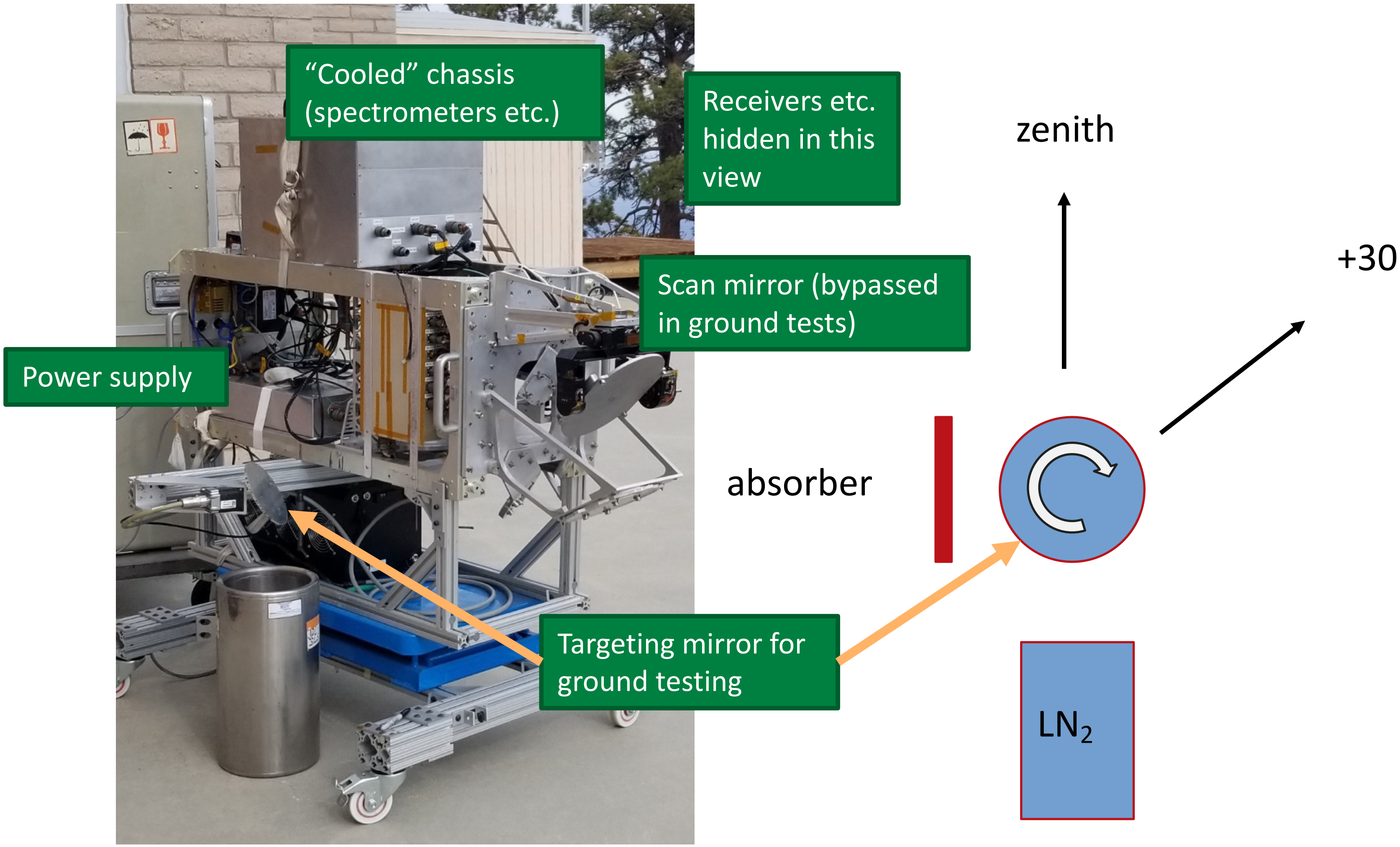
Calculated 'Limb' Spectra from ER-2 altitude



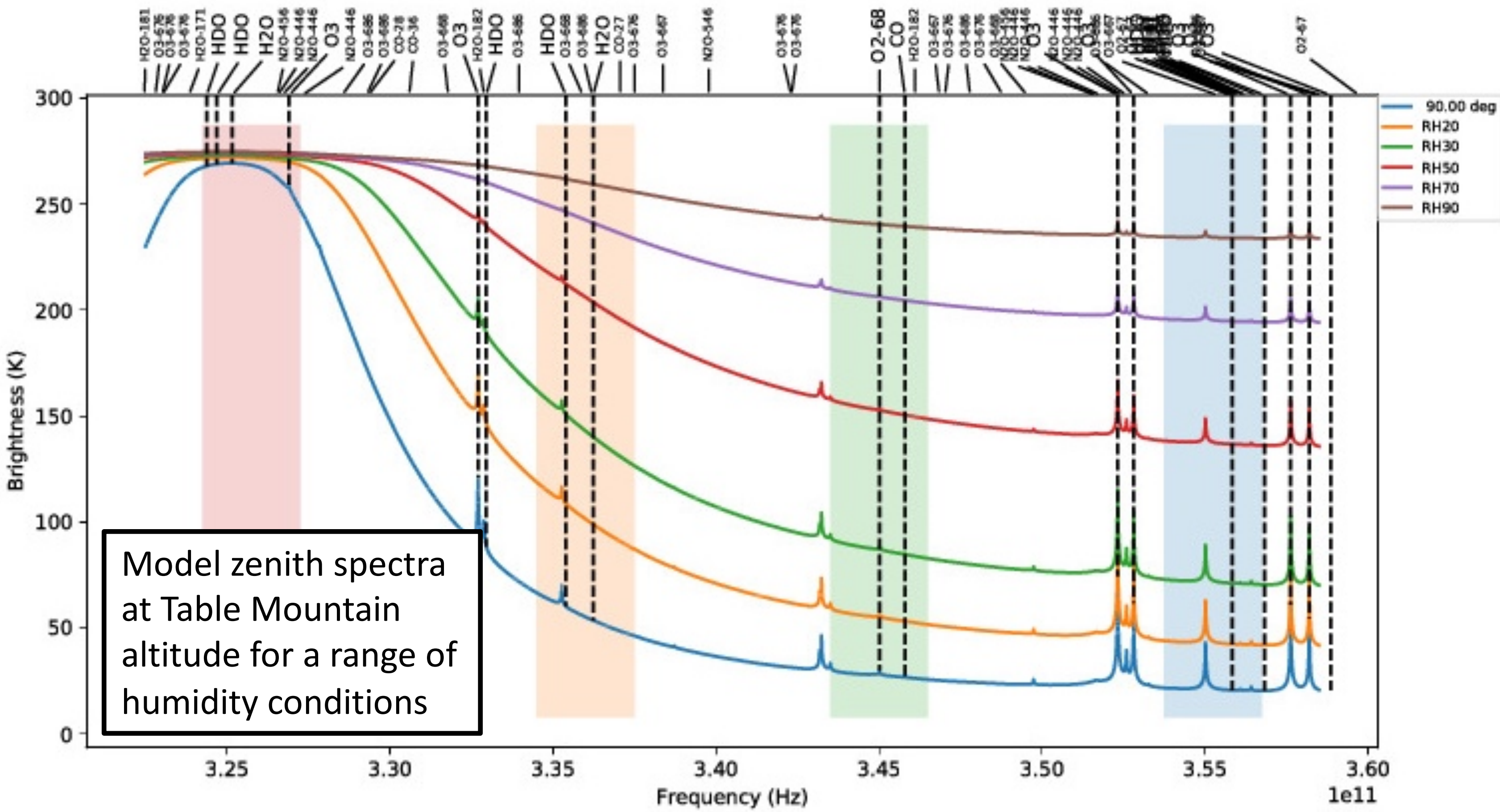
'Local Oscillator' at 340.5 GHz. Shaded regions show spectrometer coverage.

Testing at JPL Table Mountain Facility



Calculated Spectra for JPL TMF at 2280m

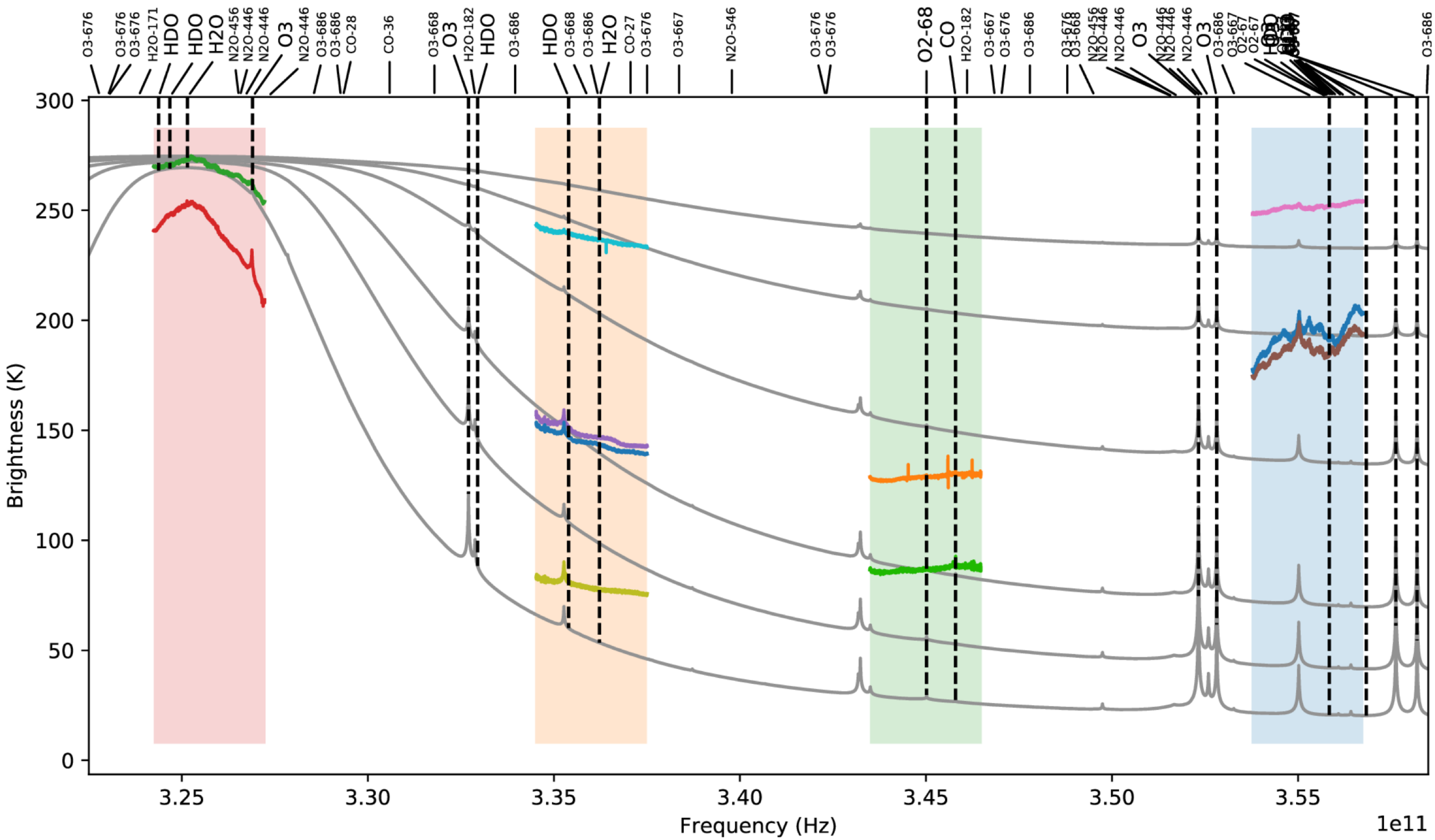
Compact Adaptable Microwave Limb Sounder



LO at 340.5 GHz. Shaded regions show normal and swapped coverage

Feb 7th, 2019 at JPL Table Mountain

Observed spectra

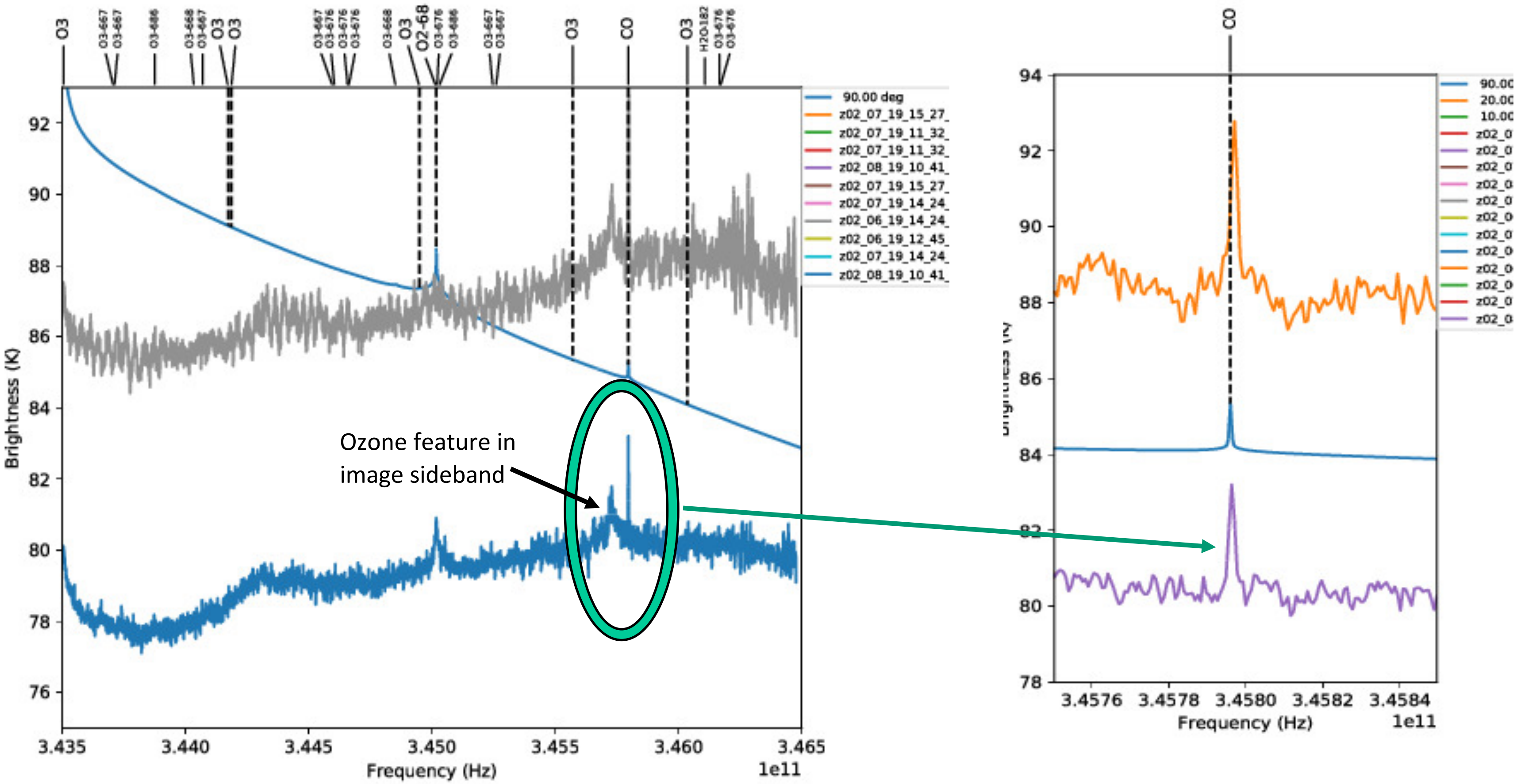


Simulated spectra (grey) for various humidities and measured spectra (colored) in 3-GHz regions for different days. (~400 s integration time.)

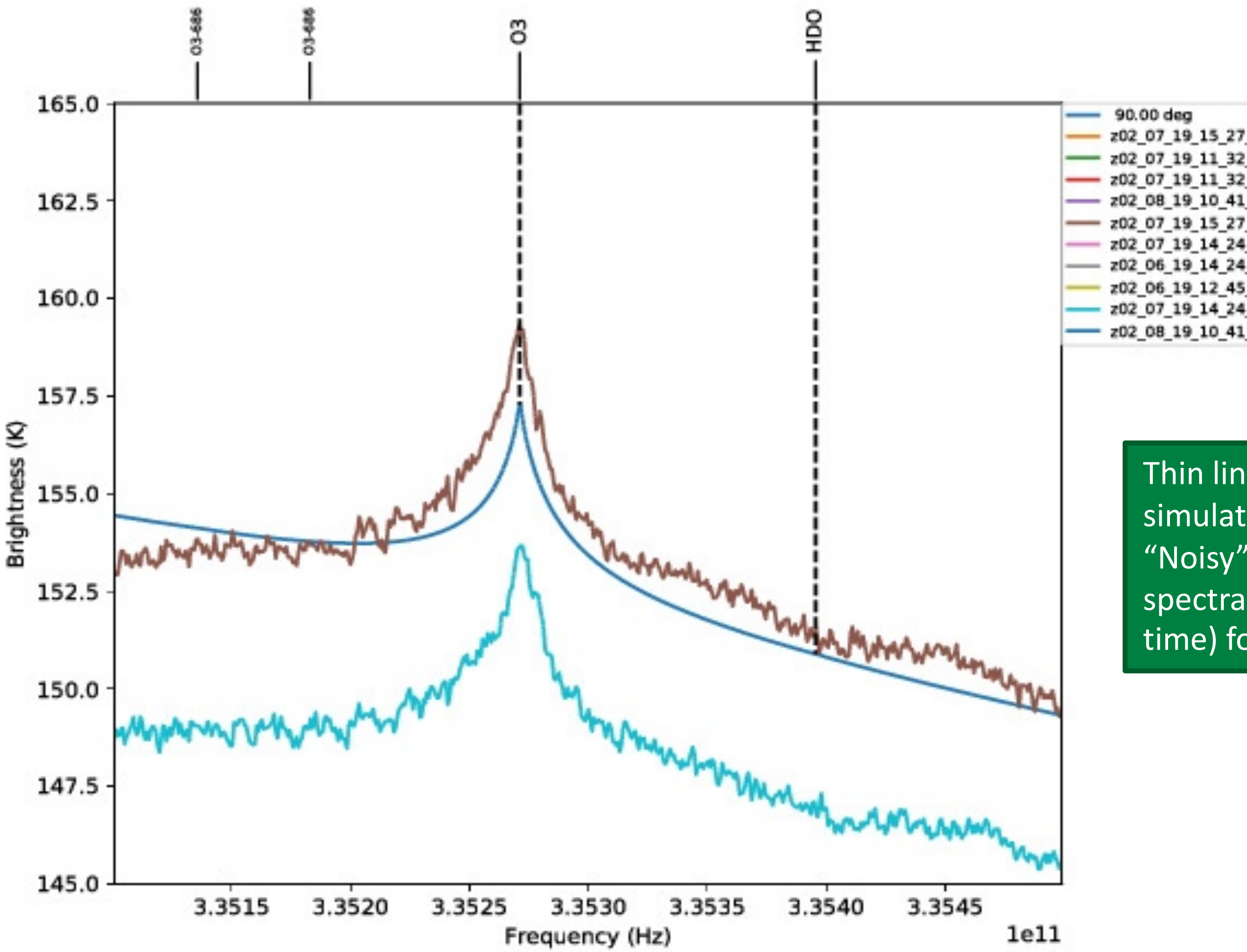
Observed spectra – mesospheric CO

Observed 3 GHz portion of spectrum with simulated spectra overlaid

Zoom in showing mesospheric CO line



Observed ozone spectra in lower sideband



Thin line is representative simulated zenith spectrum. “Noisy” lines are measured spectra (~400s integration time) for different days

Next steps

- Finalize integration into A-SMLS instrument
  - The development is essentially complete, but we are updating some structural elements to ensure compliance with ER-2 flight practices
- Perform more detailed ground-based calibration
  - With a particular focus on the sideband fractions
- Fly on NASA ER-2
  - We plan to fly in conjunction with the Canadian SHOW instrument, which targets upper tropospheric and stratospheric water vapor
  - Flights are expected to be no earlier than spring 2020 owing to aircraft availability
- Longer term (airborne): make A-SMLS/CAMLS suitable for field campaigns
  - Finalize the cooling system
  - At an “intelligent” (i.e., aircraft orientation-aware) scanning capability
- Longer term (spaceborne): Prepare for suitable opportunities
  - Earth Venture Continuity, should a call target CAMLS-like measurements
  - “Ozone and Trace Gas” Explorer opportunity, likely in collaboration with others